

# High-Frequency Propagation in the Ocean Waveguide

Michael B. Porter

Heat, Light, and Sound Research, Inc.

3366 N. Torrey Pines Court, Suite 310

La Jolla, CA 92037

phone: (858) 457-0800 email: [michael.porter@HLSResearch.com](mailto:michael.porter@HLSResearch.com)

Katherine H. Kim

Heat, Light, and Sound Research, Inc.

3366 N. Torrey Pines Court, Suite 310

La Jolla, CA 92037

phone: (858) 457-0800 email: [katherine.kim@HLSResearch.com](mailto:katherine.kim@HLSResearch.com)

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## LONG-TERM GOALS

The long-term goals are to advance our understanding of the nature of high-frequency (8-50 kHz) sound propagation in the ocean waveguide, with emphasis on surface, bottom, and volume effects on the forward-propagated field.

## OBJECTIVES

The objective of this work is to learn as much as possible about the channel impulse response (or transfer function) and its dynamics. Ideally, we would like to characterize the behavior as a function of 1) source/receiver geometry, 2) arrival angle, 3) carrier (central) frequency, 4) ocean volume structure, 5) bottom type, and 6) boundary dynamics, including effects of surface waves and bubbles. The band of interest has a variety of applications, including mine countermeasures, tracking odontocetes in navy ranges, and bottom mapping. However, the core application of interest in this program is for acoustic communications.

## APPROACH

This year's work, as usual, has examined a number of different areas, all linked by the common thread of HF acoustics. We focus on one area, namely the enhancement of the BELLHOP Gaussian beam model to model fine-scale surface roughness with greater fidelity. BELLHOP forms the core of the VirTEX (Virtual Timeseries Experiment) Model used for simulating modem performance. VirTEX in turn works directly on the modem timeseries including the time-dependent wave motion, and producing non-specular scatter. (Joint work w/M. Siderius.)

In previously reported work, we discussed how the BELLHOP arrivals information (amplitude and travel time for the echoes) could be juggled in an efficient way to simulate how a modem waveform interacts with ocean surface waves. In addition, we discussed a more sophisticated approach based on a time-domain implementation of the Kirchhoff approximation. Naturally the search for greater accuracy

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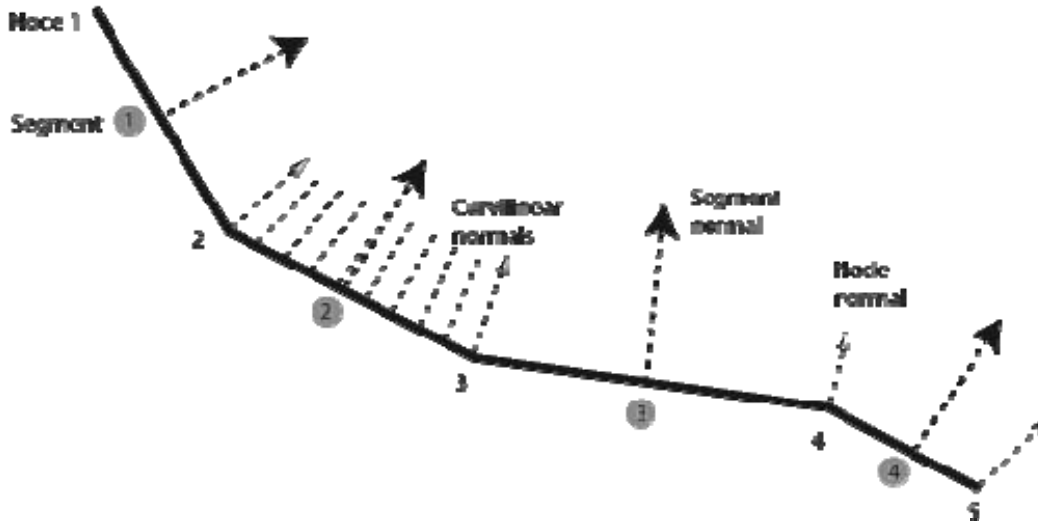
in the Kirchhoff approximation was associated with increased computer run-time. Thus we have a hierarchy of solutions which, in order of increasing run-time and accuracy, is expected to continue as follows: 1) BELLHOP/Geometric rays, 2) BELLHOP/Gaussian beams, 3) Kirchhoff Approximation, 4) Exact Helmholtz-Kirchhoff Integral Equation. A key issue was to systematically quantify the accuracy. To do this properly, we knew that we would also have to modify and carefully check the BELLHOP treatment of rough boundaries. The earlier implementation was designed for a simple piecewise-linear bottom model with large-scale features. As is well-known, ray theory breaks down as smaller features (relative to a wavelength) are introduced, so the suitability of BELLHOP for surface waves was unclear.

## WORK COMPLETED

An interesting test case for boundary interactions is the parabolic bottom profile described by McGirr, King, and Davis in their evaluation of range-dependent ray theory models. It is notable that his 1985 report concluded that *none* of the Navy's then standard ray models tested were capable of producing both satisfactory ray traces and intensities. (Twenty years is a long time, but actually there has been little investment since then, on ray or beam-based models.) Their parabolic bottom case provides an elegant test of the ray tracing accuracy and was adopted here to validate the boundary interpolation. The rays from the point source should, ideally, reflect to produce a parallel set of rays, much as the reflector in a flashlight produces a uniform beam. As we go out to 20 km or so in range, the position of the rays is extremely sensitive to the tilt of the bottom facets, and therefore an interesting metric on how well the bathymetry interpolation works.

Historically, a variety of methods have been used in ray-theoretic models to interpolate a discretely-defined boundary. A very basic approach uses piecewise linear interpolation yielding a faceted bottom. Not surprisingly, this "broken mirror" produces artifacts. Splines have often been proposed as an improvement. They produce smoother interpolates; however, in the quest to provide a smooth solution, splines often wiggle to extremes, causing their own artifacts. Splines under tension (T-Splines) have been used with greater success (Foreman, Bucker).

Our approach has been to separately interpolate the bathymetry function and its derivatives (normals and tangents). Thus we use piecewise-linear interpolation to determine when the ray crosses the boundary, but we linearly interpolate the boundary normals to calculate the angle at which the ray reflects, and the curvature change for the associated beam. This approach is illustrated in Figure 1. Note in the lower panel of Figure 2 how this improved boundary interpolation provides a set of perfectly (as far as the eye can see) parallel rays, as expected. In contrast, the faceted (or piecewise linear interpolation) produces an irregular set of rays. A final check is performed by looking at the intensity (or transmission loss) as shown in Figure 3. We see the desired smooth pattern in the Gaussian beam tracing result.

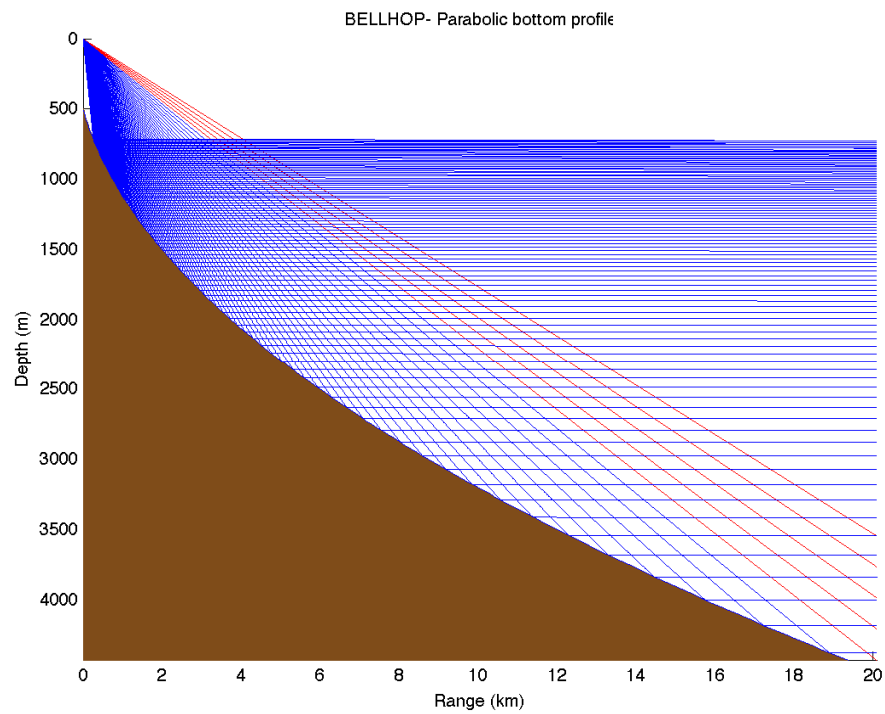
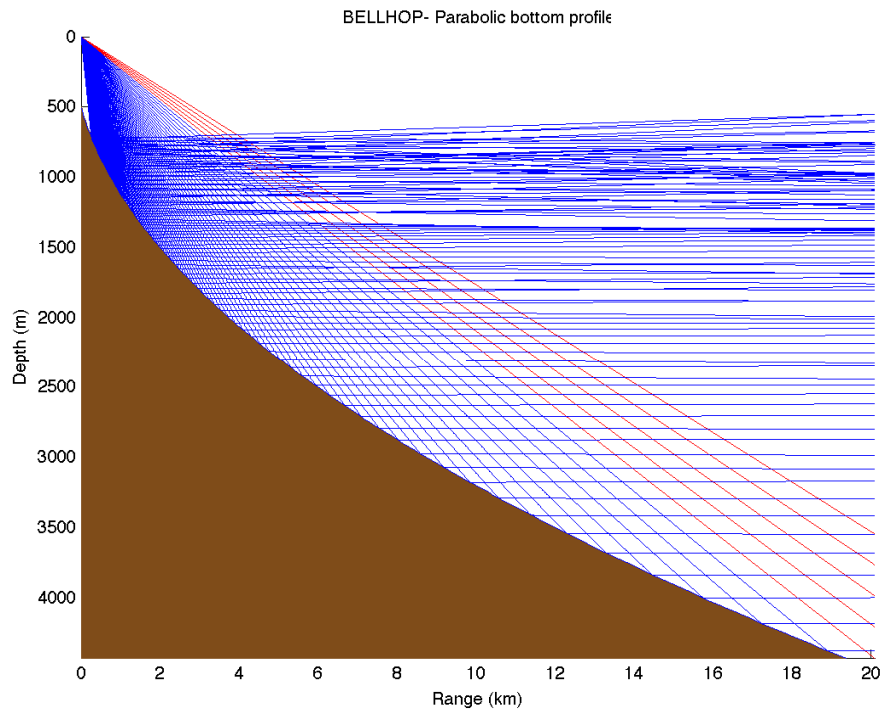


*Figure 1. Curvilinear boundary interpolation: Segment normals derived directly from the facet model; Node normals interpolated from neighboring segment normals; Curvilinear normals interpolated from Node normals.*

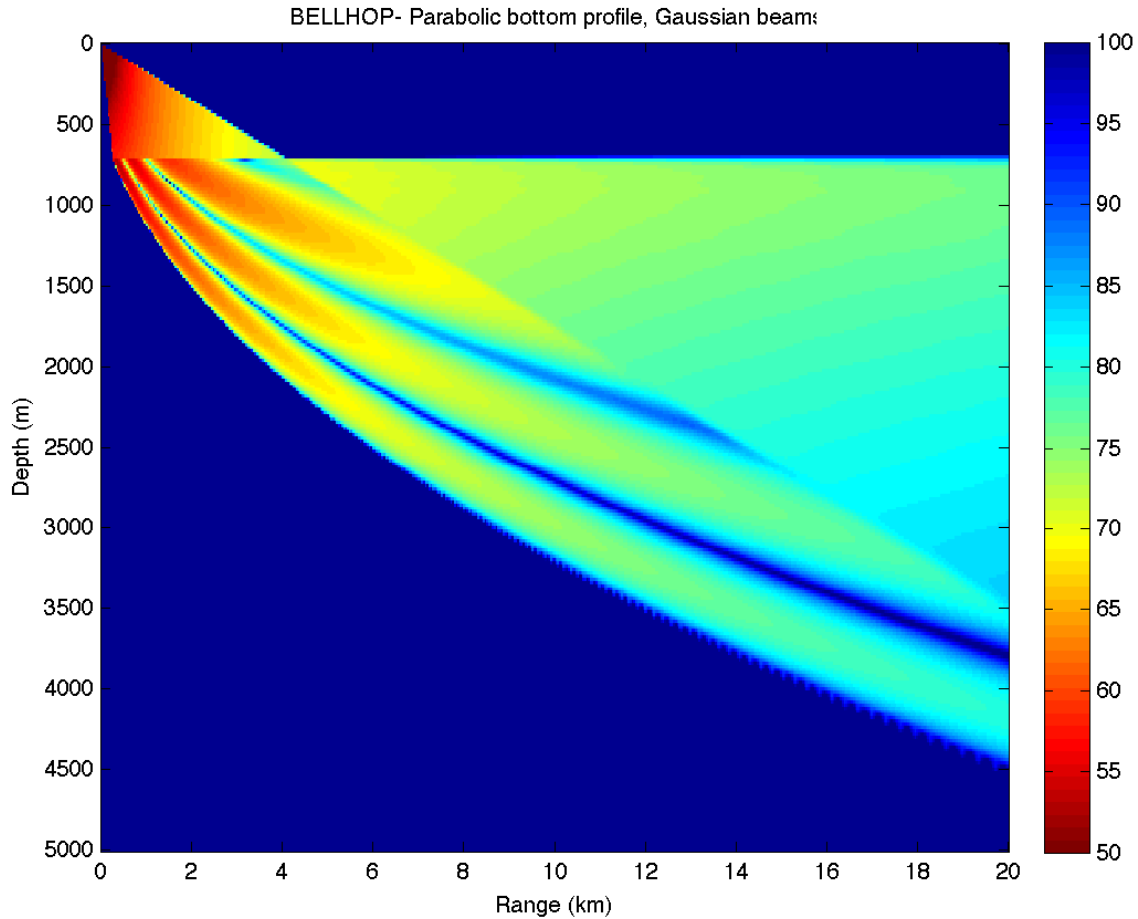
## RESULTS

With the improved boundary interpolation, we revisited some previous surface scattering cases to see how the Gaussian beam approach would do on fine scale roughness. The results are shown in Figure 3. We present a hierarchy of solutions with the most accurate (and most time consuming) at the top left. In particular, a) is the exact Helmholtz-Kirchhoff integral equation solution (following precisely a nice development by E. Thorsos). This solution is the benchmark; however, the integral equation links every point on the surface to each other and is an unlikely candidate for use in a time-series simulator. Panel b) makes the classic Kirchhoff approximation in which each point on the surface radiates according to a simple formula related to its ensonification. One can see that this approximation does well for both the gentle and rapidly varying surfaces. This Kirchhoff approximation generalizes nicely to the moving surface over a refractive medium, which is why we're particularly interested in it here.

The lower panel uses a Gaussian beam tracing approximation. This is by far the simplest and fastest approach and also easily generalizes to the moving surface problem. The surprising (to us) conclusion of this work is that the Gaussian beam approach, with careful attention to the complicated boundaries produces a result that is arguably as good as the Kirchhoff approximation. Eisenhower, it is said, once complained that he needed more one-handed scientists. There is, inevitably, another hand here which weighs the premise that the conclusions need to be verified at the higher frequencies of current interest for acoustic modems. Panel d) shows BELLHOP running in its classical geometric beam mode. We see some expected artifacts of geometric ray theory, reminding us of the limits of that approach.



***Figure 2. Comparison of piecewise-linear (upper panel) and curvilinear (lower panel) bottom interpolation for the parabolic bottom profile. The reflected rays in the curvilinear approach form a uniform set of parallel rays, as desired.***

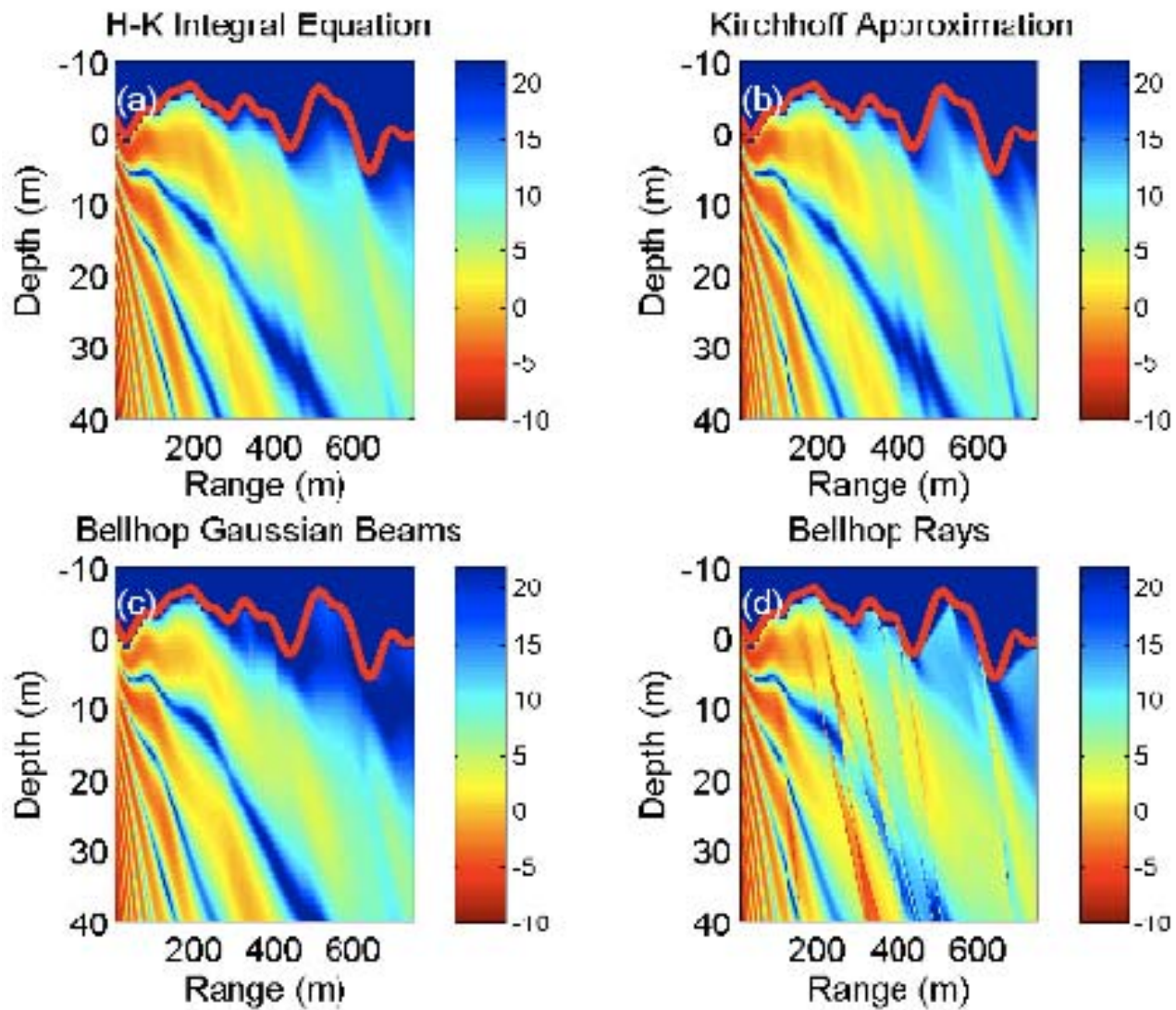


*Figure 3. Transmission loss for a 10 Hz source with the parabolic bottom profile using BELLHOP with the Gaussian beam tracing option.*

Results of this research have been submitted in two journal articles and various conference presentations. Finally, work has continued on revisions to the text *Computational Ocean Acoustics* in preparation for the new edition.

## **IMPACT/APPLICATIONS**

There are a variety of Navy systems that operate in the HF band. However, a key application of interest is acoustic modems. A validated simulation capability is critically important to future DNS (Distributed Networked Systems) exploiting this wireless technology.



**Figure 4.** Comparison of a) exact Helmholtz-Krichhoff Integral Equation, b) Kirchoff approximation, c) BELLHOP/Gaussian beams, and d) BELLHOP/Geometric beams. The Gaussian beam solution provides a surprisingly accurate solution. This implementation benefits from the curvilinear boundary interpolation. Conventional ray theory produces expected, but undesirable singularities at the caustics.

## TRANSITIONS

This work is being conducted in parallel with the 6.2 SignalEx program (322OM) on underwater acoustic communication so that lessons learned about the basic propagation physics can be immediately linked to modem performance. The SignalEx program in turn transitions to operational modem development through other 6.3/6.4 navy programs.

## RELATED PROJECTS

Work reported here is linked to other programs as mentioned above. VirTEX is being developed together with M. Siderius.

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